Civil Engineering April 1967

Building costs: lightweight concrete, stone concrete, steel

E. VERNON KONKEL, F. ASCE, President,
Ketchum, Konkel, Barrett, Nickel, Austin, Consulting Engineers
Denver, Colorado

Costs are compared of building structures designed in lightweight concrete, stone concrete, structural steel and timber. Building types examined include multi-story apartment, office and school buildings, thin shell structures (folded plate, barrel shell, and hyperbolic paraboloid), and one-story industrial buildings. Among the conclusions: In multi-story buildings, concrete of both types is less costly than fireproofed steel. In most thin-shell types, lightweight concrete is less costly than stone concrete. In industrial buildings, at lower bay widths and spans, joist and beam systems of wood and steel are least costly; at longer spans the differences are less.

Justifying the use of lightweight concrete on a basis of cost is a time-consuming task. This suggested the need for more detailed economic analysis. As a result, Ketchum, Konkel, Barrett, Nickel, Austin, consulting engineers, was commissioned by Idealite Company, a producer of lightweight aggregate, to conduct studies designed to compare and evaluate the relative economics of various structural systems and materials.

Studies were made to compare costs of building frames constructed with various materials, including lightweight concrete using coated expanded shale, stone aggregate concrete, structural steel, and timber. Building types examined included multi-story apartment, office and school buildings, thin shell structures (including folded plates, barrel shells, and hyperbolic paraboloids), and one-story industrial buildings. Complete designs and quantity takeoffs and graphs to illustrate the results were prepared.

Though more costly per cubic yard than stone concrete, a structural lightweight concrete permits using members of smaller cross-section. It may also be selected because of its lesser creep deflections as a result of the smaller dead load. Lightweight concrete's superior uniformity improves its appearance and performance.

With lightweight concrete, floor systems may be shallower; columns may be smaller, and foundations are smaller, especially when supporting soils are poor. The inherent disadvantages of stone concrete are dead weight and lack of uniformity. Lightweight concrete partially overcomes these.

It was assumed in the cost comparisons that excellent stone aggregates were readily available at minimum cost, and that excellent foundation conditions exist. Should these conditions not hold, lightweight concrete would look relatively better. Two local contractors assisted by supplying unit prices for construction in the Denver area in 1958-1962. All designs were in accordance with applicable codes.

Highlights of findings

The following general conclusions may be drawn from the study:

- In multi-story buildings, a fireproofed steel frame is more expensive than a concrete frame.
- In multi-story buildings, frames of lightweight concrete and stone concrete cost about the same, except as noted below.
- In structures having low ratios of live load to dead load, lightweight concrete has more favorable costs.
- In lightweight concrete slabs reinforced with mild steel, costs are most favorable when minimum slab depths are employed, but creep deflections must be considered. When equal slab depths are used, deadload creep deflections are less for lightweight concrete than for stone concrete.
- Lightweight concrete framing in multi-story buildings permits reductions in size of columns.
- Savings in foundations costs for lightweight concrete structures become more pronounced when poor soil conditions are encountered.
- In most thin-shell types examined, lightweight concrete results in lower costs than stone concrete. In thin shell structures using lightweight concrete, costs are minimized where a thinner shell is made possible. As spans increase in thin-shell structures, savings with use of lightweight concrete become significant.
- In industrial buildings, use of lightweight concrete is economical if thin shell or prestressed elements are to be used. At the lower bay widths and spans, joist and beam systems of wood and steel will result in lower initial costs. As the area of unobstructed floor space increases, the cost differential becomes less and concrete may be less costly.

Apartment buildings

The apartment building was designed for 20, 10 and two stories, three bays wide, indefinitely long, with spans equal in each direction varying from 14 ft to 30 ft. A 7 ft cantilever balcony was provided on both sides of the structure. The cost of full basement with 12-in. thick concrete walls was included. A clear height of 8 ft was maintained in all designs. Costs were taken from a typical interior bay extending the full width of the building.

Concrete. A flat plate system was employed for the concrete frames for

Mr. Konkel, a partner in his firm, is a past president of the Consulting Engineers Council of Colorado, the Professional Engineers of Colorado and the Structural Engineers Association of Colorado. He is a past vice president of the Consulting Engineers Council of the United States. He was named "Engineer of the Year" for Colorado in 1966.

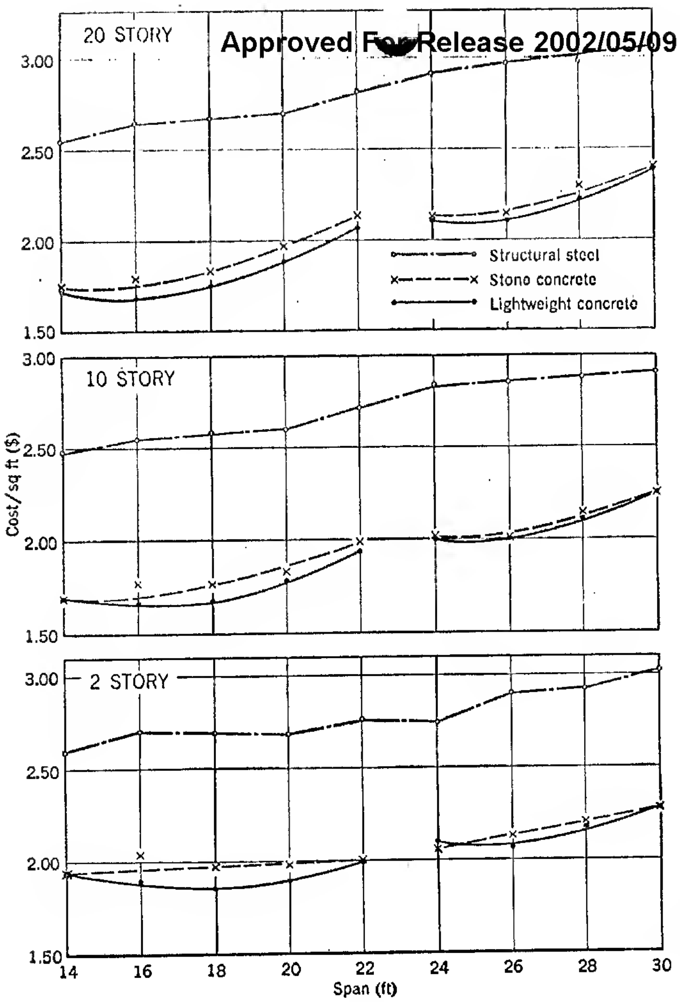


FIG. 1. Total structure costs for 20, 10 and 2 story-apartment buildings, framed in steel, stone concrete and lightweight concrete.

Table 1. Unit prices and representative extensions (14 ft bay, 20 story apartment)

Item	Unit	Unit Price	Quantity	Cost
3000 psi lw. Concrete (Slabs & Spandrel Beams)	cu. yds.	$ 17.50 + 5.00	263	$ 5,930
5000 psi lw. Concrete (Columns)	cu. yds.	19.50 + 6.00	25.3	646
3000 psi, Stone Concrete (Basement Walls)	cu. yds.	12.25 + 2.75	8.3	125
3000 psi Stone Concrete (Caissons)	cu. yds.	12.25 + 2.75	14.1	210
Reinforcing Steel (Slabs & Spandrel Beams)	pounds	0.14	45,900	6,430
Reinforcing Steel (Columns)	pounds	0.14	17,300	2,430
Reinforcing Steel (Basement Walls)	pounds	0.14	672	94
Reinforcing Steel (Caissons)	pounds	0.14	2,300	320
Forming (Slabs)	sq. ft.	0.40	16,020	6,430
Forming (Spandrels)	sq. ft.	0.60	1,136	682
Forming (Columns)	sq. ft.	0.80	2,710	2,170
Forming (Bsmt. Walls)	sq. ft.	0.50	448	224
Filler Blocks	each	8″ = 0.39 10″ = 0.45		
Caisson Drilling	ft.-diam	VARIES	120′-2′ DIAM.	150
Slab on Grade	sq. ft.	0.38	589	240
Slab Finishing	sq. ft.	0.10	[illegible]	1,630
Total Cost Per Bay				$27,711
Unit Cost (per sq. ft.)				$ 1.71

spans of 14 ft to 22 ft, and a waffle slab for the 24 ft to 30 ft spans. Analysis indicated that for purposes of strength a thinner slab could have been used for lightweight concrete, but depths used were considered the practical minimum for deflection.

Steel. A lightweight concrete slab, reinforced with and formed by corrugated steel deck on steel beams, was selected as the floor system for the steel structures. A three-hour fire rating was provided on all beams and columns, and a two-hour rating for floors. Additional sidewall costs were added in the cost summary to compensate for increased story heights required by the steel structure.

Fig. 1 gives costs for the three alternatives. Unit prices assumed in the report, and extensions for the 14-ft bay spacing (20 story building), are given in Table 1.

For the very short spans, reinforcing in the lightweight concrete slabs is governed by the maximum spacing required by code rather than by computed stresses. This precludes any savings in reinforcing steel to offset the higher cost of lightweight concrete in the same depth of slab. As the spans increase, the cost of the lightweight concrete slab increases at a more rapid rate than the cost of the stone concrete. This is due to the higher unit price being applied to the larger volumes. The effect is to make the lightweight concrete cost curve approach that of the stone concrete. This is somewhat offset by the savings in the column reinforcing. As the number of stories decreases, the column savings diminish and the lightweight concrete cost curve approaches the stone concrete curve. The extreme position of the stone concrete point at 16 ft is largely because specified minimum column steel is more than required structurally.

Office building

Our study indicated that structural costs of the lightweight concrete frames for office buildings tend to be slightly higher than stone concrete used in similar frames in apartment buildings. The same basic structural system was used in the concrete structures for the office building study as in the apartment building. The steel structure was similar to that for apartments, except that cellular steel deck, available for electrification, with lightweight concrete fill was used.

No graph is included herein, but the office building cost curves follow closely those of the apartment buildings, and the same discussion is applicable. The lightweight concrete costs are slightly higher than those of stone

concrete; this may be attributed to the higher live load/dead load ratio. There are many cases where lightweight concrete is economical for office buildings, especially where the spans are large.

School building

The school building was designed as a three-story structure, indefinitely long and three bays wide; a center corridor bay of 16 ft and two classroom bays varying in width from 20 ft to 30 ft in 2 ft increments was considered. The span of each bay in the longitudinal direction was kept constant at 16 ft. A clear height of 9 ft-6 in. between stories was maintained. Costs were taken from a typical interior bay extending the full width of the building.

Concrete. A one-way concrete joist system with shallow interior beams was used to frame the lightweight and stone concrete structures. Lightweight concrete block fillers were used to provide forming and a continuous soffit for direct application of paint or plaster. A ½-in. plaster ceiling was considered for design loads but not included in the cost summary.

Steel. A corrugated steel deck with concrete fill was used as the floor system for the steel building. A lightweight insulating fill was used as topping for the roof deck. Standard open web steel joists framing onto center and spandrel beams support the steel deck. Rolled sections were substituted for joists at the column centerlines for lateral load resistance.

Beams and columns were fireproofed to provide a three-hour rating. A plaster ceiling was provided to fire rate the floor and roof for two hours. Fig. 2 shows the cost comparison. The use of lightweight concrete in this type of framing results in slightly higher costs than with stone concrete. As the spans increase, the saving in reinforcing steel offsets the increased cost of lightweight concrete. The study was made for a typical classroom wing. There are many times where lightweight concrete may be used to advantage in schools.

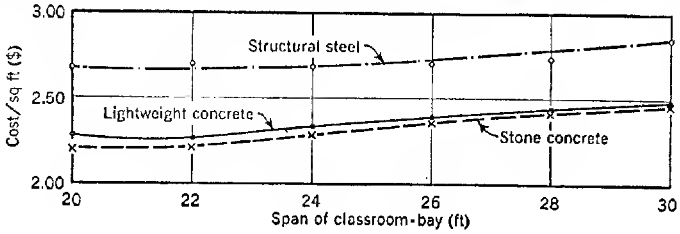


FIG. 2. Total structure costs, school building of three stories, three bays.

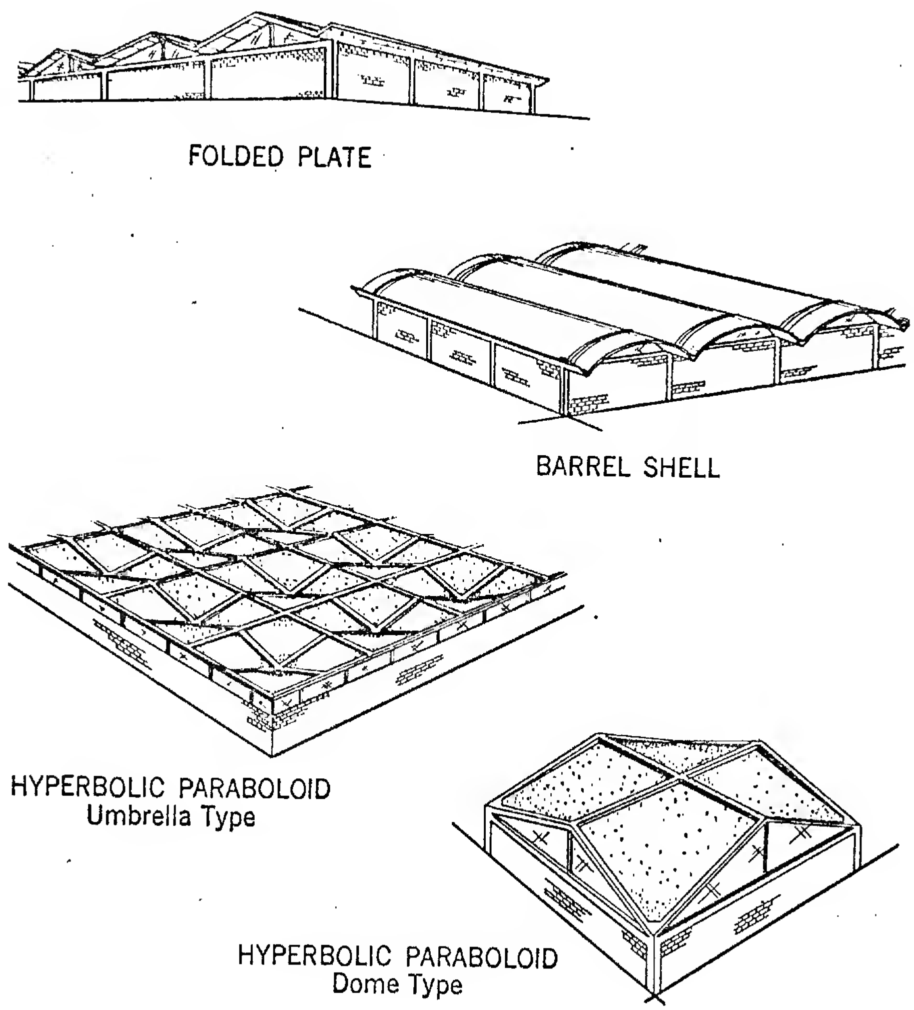


FIG. 3. Types of thin-shell roofs studied.

Thin shell structures

Four representative types of thin shell concrete structures were selected for study: folded plates, cylindrical barrel vaults, and two forms of hyperbolic paraboloids. Fig. 3 shows the configurations. This study determined that in almost all designs investigated, lightweight concrete proved to be more economical than stone concrete. As the spans increased and the thickness increased, the savings of lightweight concrete is significant. For short spans, where minimum requirements for reinforcing steel and concrete govern, costs for lightweight and stone concrete are approximately equal.

Folded Plates. The folded plate structures consisted of single spans with five bays forming a roof having a continuous two-element fold. The spans considered were 20 ft by 40 ft, 25 ft by 50 ft, and 60 ft and 80 ft span each with a bay width of 30 ft. The pitch was held in a 4-in-12 for all spans except the 80 ft span which required a 3-in-12 pitch to provide a practical design. A clear height of 12 ft was provided.

Designs were made for only a typical interior bay. Edge members and side walls were included in the cost takeoff as a separate item, in order to obtain the total cost of a five-day building. Fig. 4 shows the cost comparison.

The cost of the structure for lightweight concrete is less than that of stone concrete throughout the span range, the maximum savings occurring for the longer spans. In a typical bay with a span of 80 ft, the lightweight concrete realizes a savings of approximately 8½ percent in the total framing cost. The reduction in reinforcing steel, due to the lesser dead load and particularly the reduction in

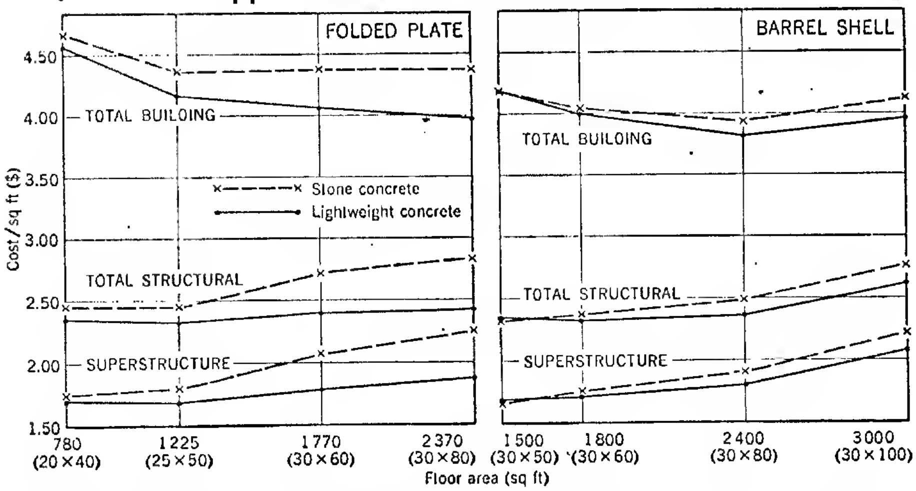


FIG. 4. Folded plate and barrel shell roofs—costs for superstructure, total structure, and total building.

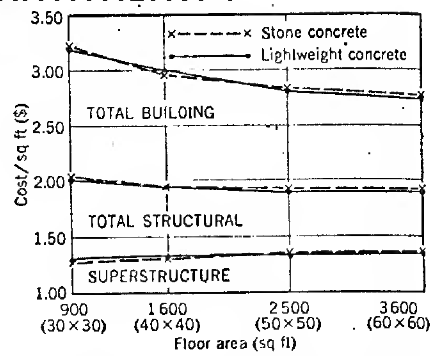


FIG. 5. Hyperbolic paraboloid (umbrella) roofs—costs for superstructure, total structure, total building.

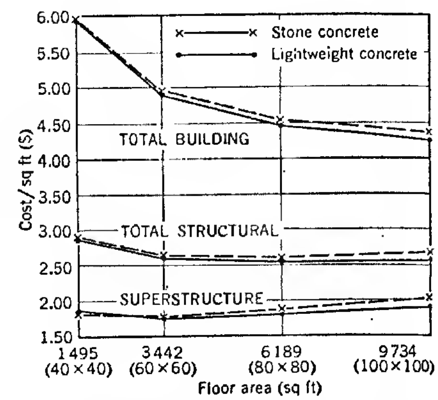


FIG. 6. Hyperbolic paraboloid (dome) roofs—costs for superstructure, total structure, total building.

the required thickness of slab, enabled the folded plate structures to have the most favorable cost difference for lightweight concrete of the four designs investigated.

Barrel Shells. The cylindrical barrel shells are of single spans with five bays. Span lengths considered were 50 ft, 60 ft, 80 ft, and 100 ft. Bay widths were kept constant at 30 ft. A clear height of 12 ft was provided. As in the case of folded plates, designs were based on a typical interior bay. Edge members and side walls were added to obtain the total cost of a five-bay building.

Fig. 4 shows the cost comparison. In the longer spans, the lightweight concrete shows a lower cost. Similar to the folded plates, as the spans become shorter, the savings decrease. Savings in cost for the shell of the cylindrical barrel vaults are gained through lightweight concrete by a reduction in reinforcing steel in the shell and tie beams. No reduction can be realized in slab thickness; therefore, the savings are less than those with folded plates.

Hyperbolic paraboloids

Two types of hyperbolic paraboloid structures were considered: the inverted umbrella which consists of a series of symmetrical bays placed five bays together in each direction, and the dome, which consists of a single larger unit. The umbrella type was supported by a single column at the center of each bay; the dome type required four columns per unit, one at each corner. For the umbrella type we investigated typical bay sizes of 30 ft, 40 ft, 50 ft and 60 ft square. The designs of the dome type had square bays of 40 ft, 60 ft, 80 ft and 100 ft. A rise of 3-in-12 was used in both types.

Designs and costs for the umbrella structure were based on a typical interior bay with exterior side walls added separately to obtain the total cost of a twenty-five bay building. The costs for the dome type structure, consisting of a single bay, represent the entire building. Cost comparisons for the umbrella are shown in Fig. 5, and for the dome in Fig. 6.

The use of lightweight concrete results in no appreciable savings for any of the umbrella type hyperbolic paraboloids. In this particular type and size of shell, the amount of reinforcing is usually minimal. Thus, the use of lightweight concrete does not permit a corresponding reduction in steel or shell thickness. It is worthy of note that the cost of lightweight concrete is competitive with the cost of stone concrete in these structures due to the savings in tie beams, columns and foundations.

The cost of a lightweight concrete structure is less than that of stone concrete for the dome type hyperbolic paraboloid. Designed as single units, larger bay spacings were chosen than for the umbrella types. Even with the larger spans, the amount of steel and thickness of concrete in the membrane is governed by minimum requirements. The savings in both steel and concrete in the stiffener and the tie members becomes appreciable, and with the reduction for columns and foundations, the lightweight concrete is lower in cost than stone concrete. As the spans lengthen, the savings for lightweight concrete increases.

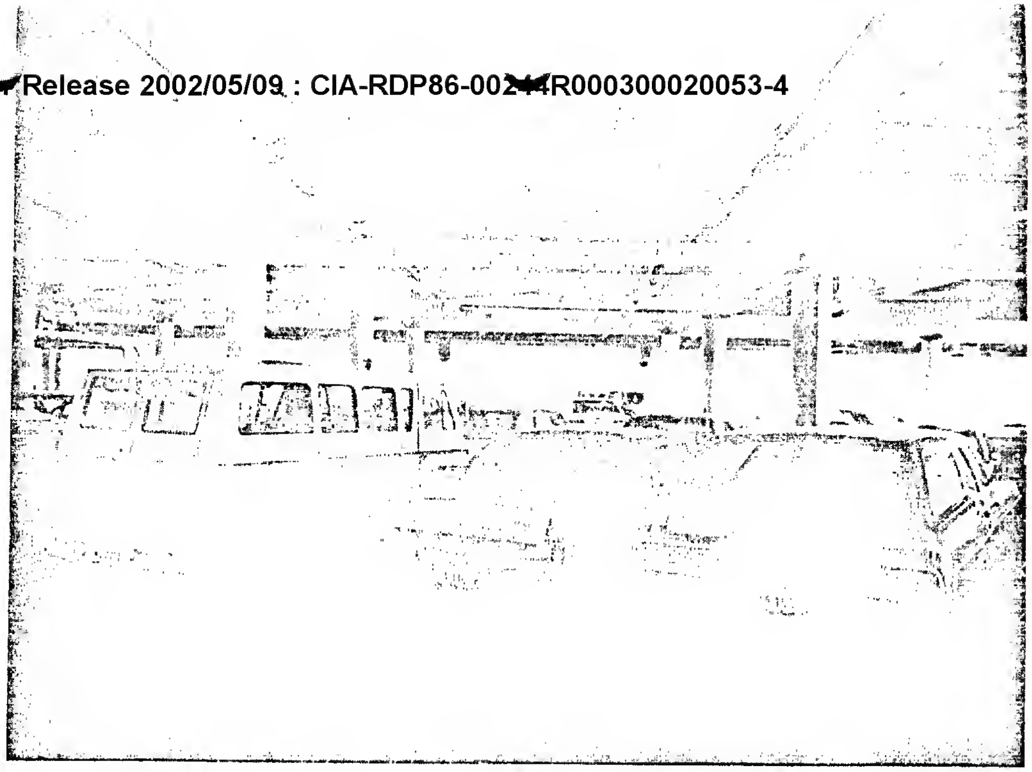
The photo illustrates a new use of hyperbolic paraboloids.

Industrial buildings

Nine structural systems were considered for industrial buildings. Five use wood or steel as the framing materials; four use lightweight concrete. For purposes of this paper, "industrial buildings" is meant to encompass one-story structures used for warehousing, manufacturing, and similar operations requiring large unobstructed floor areas.

The comparison indicates that the initial cost of a lightweight concrete structure may be only slightly more than the most inexpensive steel or wood system. Further, the cost differential between the concrete and wood or steel systems decreases as column free floor areas increase. When consideration is given to many intangibles, the use of lightweight concrete may well result in an economical solution to the industrial building.

The basic unit selected for comparison consisted of a typical interior bay of a building three bays deep with various spans. Bay widths shown on Fig. 7 are 20 ft, 30 ft and 40 ft with the span lengths varying from 30 ft to 100 ft. Each width was combined with all of the spans. Some combinations of widths and spans resulted in impractical arrangements for certain systems and were excluded from the comparisons.



Parking garage at Chase Stone Center, Colorado Springs, Colo., incorporates an innovation in floor slab design—the underside of the slab is a hyperbolic paraboloidal surface, while the top side is, of course, flat. Slab thickness is 24 in. at the columns and 7 in. at midspan (30 ft spans in both directions). Due to the proportions of the slab, positive moments are very small; thus the post-tensioned cables are straight. This means no resulting loss in tensioning due to friction, which permits making the cables twice as long as in a draped-cable structure; thus, about half as much end hardware was used as normally in a typical two-way slab with draped cables. Result: a very economical structure.

Following is a key to each system:

1. *Timber frame:* Bowstring wood trusses on wood columns at bay spacing; 20 ft bay—wood joists 24 in. on center, ⅜ in. plywood sheathing; 30 ft and 40 ft bays—wood purlins 8 ft on center, 2 in. wood tongue and groove lumber.
2. *Steel frame:* Steel rolled sections on steel columns at bay spacing. (a) 20 ft bay—*wood joists* 24 in. on center, ⅜ in. plywood sheathing; (b) 30 ft and 40 ft bays: *wood purlins* at bay spacing, 2 in. wood tongue and groove lumber.
3. Steel frame at bay spacing, *steel purlins* at 8 ft on center with steel deck.
4. Steel frame at bay spacing, *open web joists* up to 8 ft on center with steel deck.
5. *Concrete, precast pretensioned beams,* at bay spacing with twin-tee roof sections.
6. *Concrete, barrel shell,* at bay spacing.
7. *Concrete, folded plate,* at bay spacing.
8. *Concrete, hyperbolic paraboloid,* special square bays. This system is most efficient when a square plan is employed. It does not lend itself to the basic spans of the other systems. It provides an economical solution to the industrial building with square bays of 30 ft, 40 ft, 50 ft and 60 ft and is shown that way.

Fire insurance costs for the industrial buildings were included as direct costs chargeable to the structural frame. It was assumed that all concrete systems could be classified as Type I or fire-resistant construction, and non-fireproofed timber or steel systems as Type III or non-fire-resistant construction. The difference of $0.38 per sq ft was added to the total cost of systems 1 through 4 inclusive which was reasonable for comparison purposes. Fig. 7 shows comparative costs of the systems. ▽

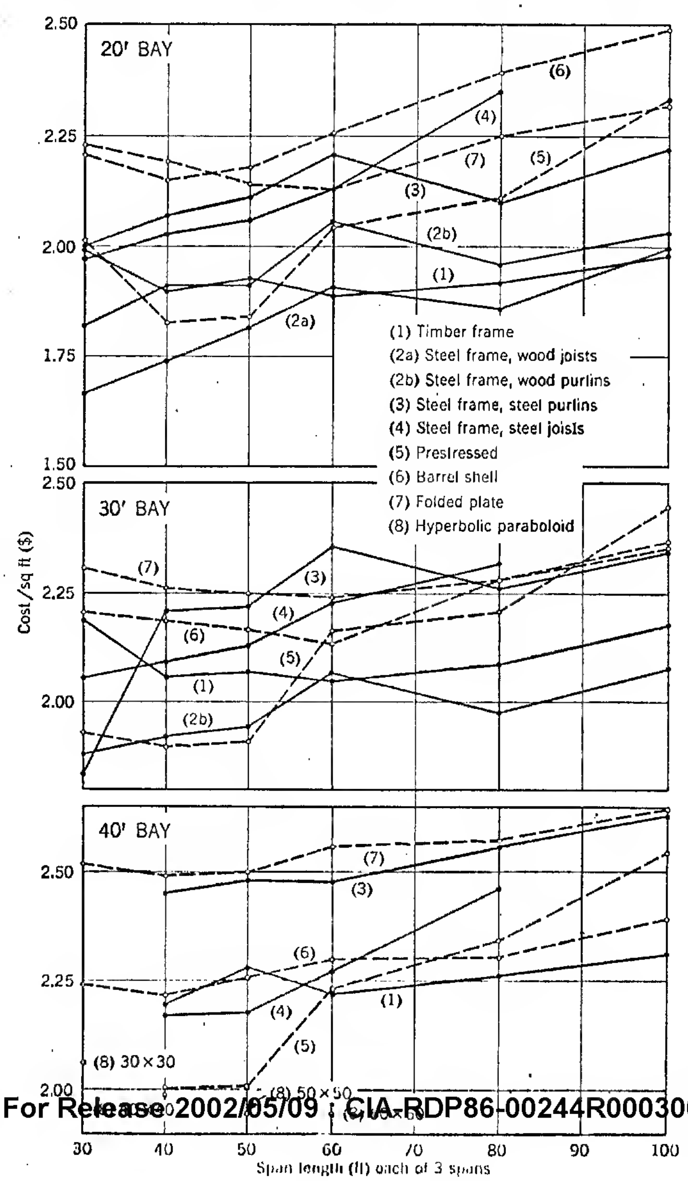


FIG. 7. Cost of industrial building designs, 20, 30 and 40 ft bay width.